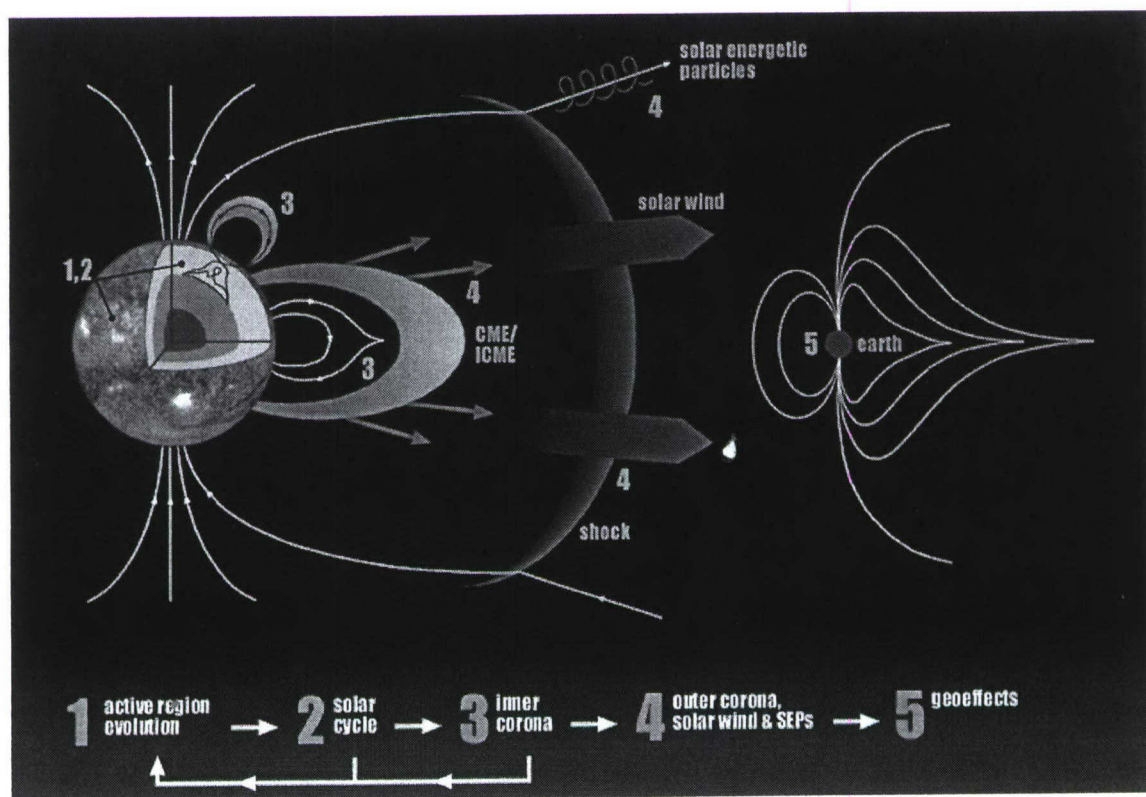


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**“Understanding Magnetic Eruptions on the Sun and their  
Interplanetary Consequences”**



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Space Sciences Laboratory  
University of California



## I. Introduction

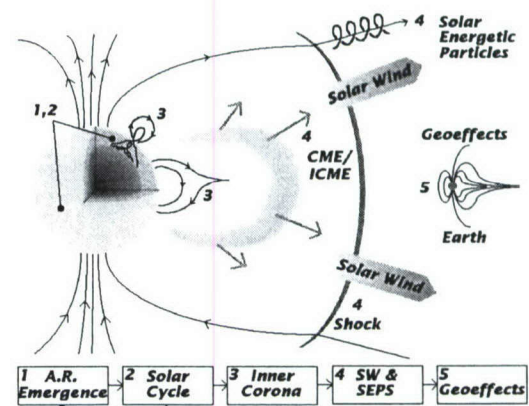
A major goal of our MURI project was to develop a state-of-the-art, observationally-tested 3-d numerical modeling system for predicting magnetic eruptions on the Sun and their interplanetary consequences.

This project is motivated by the fact that the Sun drives the most violent space weather events. The mechanisms that trigger and drive these eruptions are the least understood aspects of space weather. A better physical understanding of how magnetic eruptions occur and how these disturbances propagate will surely lead to more accurate and longer range forecasts.

Our team consisted of a consortium of about 25 scientists from 9 Universities. In addition to UC Berkeley, our team included scientists from the University of Hawaii, Stanford University, the NJIT Big-Bear Solar Observatory, UC San Diego, Montana State University, the University of Colorado, Drexel University, and the University of New Hampshire.



**Figure 1 - The 9 US Universities that are a part of our MURI project.**



**Figure 2 - Diagram illustrating the Sun-Earth system and its schematic relationship to CMEs.**

To what extent was our project successful, in the sense that we were able to achieve the above goal?

We have not (nor has anyone else thus far) been able to use a physics-based solar model, using the observed evolution of real, observed solar magnetic field data, to initiate a CME and to have it propagate from the lower solar atmosphere, through the corona, and into the heliosphere. We think it is important to acknowledge this, and to pinpoint the primary reason for it: Our scientific community's collective lack of understanding of the physics of how CMEs are initiated, and perhaps more importantly, how the magnetic configuration in the solar atmosphere builds up into a pre-eruptive configuration. Until this understanding is achieved, the goal as stated above will not be met.

Having said that, we nevertheless regard this MURI project as a spectacular success. Over the course of the past 5 years, we have shown how many parts of the overall problem can be solved. Our team members at MSU and UC Berkeley have created a new paradigm in solar physics for the use of magnetic field data in driving numerical simulations of the solar atmosphere, and have developed completely new numerical techniques capable of incorporating the plasma at the photosphere and below, while simultaneously evolving the solar corona. Our approach to the outer coronal and heliospheric modeling part of the CME propagation problem, formulated by Zhao



and his colleagues at Stanford and carried out by Odstrcil at the University of Colorado, has proven so successful that it has been adopted wholesale by the CISM space-weather modeling effort. Our instrumentation efforts at UH and NJIT/BBSO funded by this MURI have achieved completely new observational capabilities, such as measuring magnetic fields in the corona with great sensitivity, and achieving extremely high spatial resolution observations of the Sun from ground-based instruments. And while we still do not completely understand the build-up to CME eruption and the initiation process, UNH and Drexel University team members have made great strides in understanding the CME initiation process. Our UCSD team members, in collaboration with their Air-Force colleagues, have shown with SMEI data that valuable information on the heliospheric transport of ICME plasma can indeed be made using space-based white-light measurements.

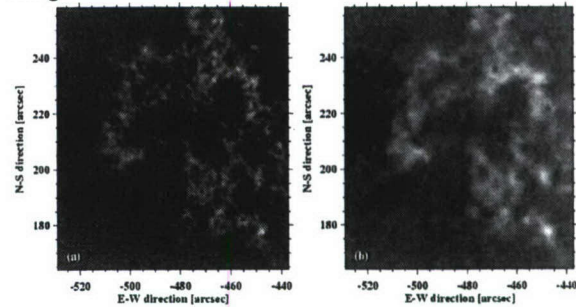
In summary, the work we have done over the last 5 years has laid the foundation for useful, predictive models of the solar atmosphere and heliosphere.

The remainder of this final report is divided into 8 sections, describing strategic observing developments, strategic computing developments, the use of vector magnetograms to determine flow fields or electric fields, the buildup of energy in eruptive active regions, CME initiation physics, CME propagation observations and modeling, and finally SEP acceleration by CMEs. Following these descriptions is a list of publications identified at this time as being at least partially supported by this MURI grant.

## II. Strategic Observing Capabilities: New Technologies Developed with support from this MURI award

**IRIM:** The Infrared Imaging Magnetograph (IRIM) developed by the Big Bear Solar Observatory (BBSO) has been put into preliminary operation. It is one of the first imaging spectro-polarimeter working at the Fe I 1.5649  $\mu\text{m}$  line, and is used for the observation of the deepest photospheric layers. IRIM combines the advantages of the

infrared Zeeman sensitivity with the capability of spatial mapping. It provides a promising tool to probe the small-scale magnetic features.



**Figure 3 - (a): IRIM magnetogram taken at 16:02 UT. (b) MDI magnetogram taken at 16:00 UT (Cao et al., 2006).**

A three-stage tandem system including a 42 Å interference filter, an unique 2.5 Å birefringent Lyot filter and a Fabry-Perot etalon is capable of providing a bandpass as low as 0.1 Å in a telecentric configuration. A fixed quarter wave plate and a nematic liquid crystal variable retarder are employed for analyzing the circular polarization of the Zeeman components. The longitudinal magnetic field is measured for highly Zeeman-sensitive Fe I line at 15648.5 Å (Lande factor  $g=3$ ). The polarimetric data, with a field of view  $\sim 145'' \times 145''$ , were recorded by a  $1024 \times 1024$  pixel, 14-bit HgCdTe CMOS focal plane array camera. Benefiting from the newly developed Adaptive Optics (AO) system, the first imaging polarimetric observations were made at the diffraction limit on 2005 July 1 using BBSO's 65 cm telescope (Cao et al. 2006).

Figure 3 shows the magnetogram from IRIM (left) in comparison with the magnetogram from MDI (right). It is clear that the magnetogram from IRIM reveals the small-scale features with sub-arcsecond resolution.

### High Resolution Imaging Technologies:

An X-10 white-light flare in solar NOAA active region 10486 was observed with the Dunn Solar Telescope (DST) at NSO/SPO using instrumentation and techniques developed at NJIT. This is the first report of a white-light flare observed at the opacity minimum. The data benefited from the AO system and a state-of-art NIR complex metal